How Will Galileo Improve Positioning Performance?

Gérard Lachapelle, M. Elizabeth Cannon, Kyle O'Keefe, and Paul Alves

The University of Calgary, Department of Geomatics Engineering

Combining signals and observables from GPS and Galileo will enable users to improve both the accuracy and the reliability of position solutions.

Gérard Lachapelle *is professor and head of the Department of Geomatics Engineering, University of Calgary, where he also hold a CRC/iCORE Chair in Wireless Location. He has been involved with GPS research, development, and testing since 1980 and has made numerous related contributions. He has received numerous awards for his contribution.*

M. Elizabeth Cannon *is professor in the Department of Geomatics Engineering, University of Calgary, where she also holds an NSERC Steacie Fellowship. She has been involved with GPS research, development and testing since 1984 and has made numerous related contributions. She has received numerous awards for her contribution, including the Johannes Kepler Award of the Institute of Navigation in 2001.*

Kyle O'Keefe *is a Ph.D. candidate in the Department of Geomatics Engineering at the University of Calgary. His major research interest is navigation satellite constellation design and performance. He has been involved in positioning and navigation research since 1996.*

Paul Alves *is a graduate student in the Department of Geomatics Engineering at The University of Calgary. His research is focused on carrier phase ambiguity resolution techniques using multiple reference stations, carrier frequencies, and advanced error modelling.*

Over the next six years, the European Union (EU) and the European Space Agency (ESA) plan to deploy Galileo, Europe's new civilian-managed Global Navigation Satellite System (GNSS). The existence of a second fully operational GNSS promises to provide substantial benefits to civilian users worldwide. Successful deployment of Galileo will more than double the number of GNSS signals in space available to users.

This large increase in satellites will benefit not only single-point accuracy but also position reliability and the ability of GNSS user equipment to resolve integer ambiguities when using carrier phase tracking techniques. With two independent but compatible GNSSs available, users will be able to exploit this situation by choosing one of three different approaches:

Use one system only. This may indeed be what happens, particularly for military and government users. The United States, having invested heavily in creating the GPS, may mandate that public agencies use only GPS. Likewise, the European Union may insist that European agencies use only Galileo for certain applications.

Use one system as a check for the other. Even if users are only navigating with one system or the other, if they are equipped with dual system receivers, or separate GPS and Galileo receivers, they will be able to compute a completely independent solution using the other system as a check for the primary system.

Combine observations from both systems. In this case, users would include observations from both systems when determining a navigation solution.

This article examines the first and third of these options from a civilian user's point of view, that is, the use of GPS alone versus that of GPS and Galileo observations in a combined solution. In our discussion, we will demonstrate that, although proponents of one system or the other often speak of their system as a self-contained alternative to the other, users can best realize the real advantages of having two compatible GNSSs when both systems' signals and observables are combined.

The benefits of more GNSS signals in space include improved availability, particularly in urban canyons and steep terrain in which signals can be blocked, as well as greater accuracy. Gains in accuracy are usually associated with the improved satellite geometry of combined GNSS constellations, which reduces the dilution of precision (DOP) and the latter factor's multiplicative effect on ranging errors. As we discuss later in the article, however, the redundant observations possible with more satellites also enable receivers in carrier-phase tracking mode to average measurement noise more effectively and, consequently, to make the position solution more precise.

Multiple Benefits

Although accuracy and precision are often cited as the primary performance measurements for a navigation system, they are meaningless metrics if the GNSS solution is highly susceptible to undetected measurement blunders or faults. In many uses of GNSS, the reliability of position solutions is as important as its accuracy. By reliability, we are referring to the ability of a system to detect and eliminate gross errors during its operation. This is particularly true for safety-of-life applications, such as aviation and marine navigation, or for demanding single-point and differential positioning.

Reliability also can be very helpful for robust, rapid, and accurate resolution of the integer ambiguities in GNSS carrier-phase tracking techniques used for real-time kinematic (RTK) and other high-accuracy applications. More generally, reliability is increasingly desirable to improve the cost effectiveness of all applications.

The sidebar entitled **"Error Detection and Reliability"** defines and explores the concept of statistical reliability, which is one of the key performance measures used in our analysis. With that tool in hand, we can then assess the reliability advantages of using combined GPS/Galileo and review some ambiguity resolution issues, including examples of the kind of signal-processing improvements that occur with a combined GNSS system.

Availability Reliability Simulations

If the constellation geometry and ranging accuracies are known, we can estimate the positioning accuracy and reliability of a GNSS. Because we do not need actual measurements in order to accomplish this, the accuracy and reliability of a GNSS can be easily simulated.

Until its sponsors finalize the design of the Galileo system, however, we need to make some assumptions about the ultimate configuration of the Galileo constellation. **Table 1** shows the design parameters that we used to simulate each constellation (GPS and Galileo). Although two more civil signals will become available on Galileo and new GPS satellites in the near future, our analysis focused primarily on the L1/E1 frequency centered at 1575.42 MHz. While we did not employ these second and third frequencies to generate results, their advantage is discussed later on.

TABLE 1 Single frequency system parameters for GPS and Galileo models used herein.

	GPS model (actual system)	Galileo model
Number of Satellites	27	30
Number of Planes	6	3
Spacing in Planes	Uneven	Evenly spaced
Inclination of Planes	53-56 degrees	54 degrees
Radius of Orbits	26,561.75 km	29,378.137 km
Frequencies Used Herein	L1 (1575.42 MHz)	E1 (1575.42 MHz)

The Galileo satellites will be deployed in three orbital planes. We assumed the positions of these planes as having arbitrary right ascensions of 0°, 120° and 240° but employed actual values for the GPS constellation. Even spacing of the Galileo orbital planes between the GPS orbital planes would have been desirable as it would ensure a maximum distribution of satellites in the sky and thus provide the strongest positioning geometry. However, in practice this cannot be maintained because the planes of the two constellations will have different orbital radii and, therefore, will precess at different rates.

Dilution of precision (DOP) and horizontal probable errors (HPEs) can easily be calculated from satellite geometry alone. All that we need to know is the position of the user, the positions of the satellites, and an elevation mask value. To compute the maximum position error due to one marginally detectable blunder, a value for the User Equivalent Range Error (UERE) must be assigned. The UERE partly depends on whether the user is in single-point or differential mode. In the examples presented here and shown in **Figures 1-4**, the HDOP and HPE values are calculated at 1-minute intervals over a 24-hour period at points located around the earth at 5-degree spacing. Heights are constrained with a standard deviation of 2 meters. We represent the results using the 50th percentile or median values of HDOP and HPE.

Figure 1 shows results for GPS alone using a 30° elevation mask in conjunction with a height constraint. We selected this particular scenario because it simulates

Error Detection and Reliability

Statistical reliability theory was developed to assess the ability of a system to detect and eliminate gross errors or blunders. (For a detailed discussion of reliability theory, see the text by K. Koch listed in the "Further Reading" section at the end of this article.) Reliability can be subdivided into internal and external reliability. Internal reliability refers to the ability of the system to detect a fault through the statistical testing of the least squares residuals on an epoch-by-epoch basis. The largest such blunder is called the marginally detectable blunder (MDB). The external reliability of a system is quantified by the size of the error in the navigation solution that is caused by a marginally detectable blunder.

In least squares estimation, it is assumed that the residuals are normally distributed. If a blunder is present in an observation, its residual will be biased but will remain normally distributed. Note that for meaningful residuals to occur, redundancy of observations is required. The least squares residuals are given by Equation 1:

$$\hat{r} = -C_{\hat{r}} C_l^{-1} w = -Rw \qquad (1)$$

where *Cr* is the covariance matrix of the residuals, *Cl* is the covariance matrix of the observations and w is the misclosure. *R* is the redundancy matrix. The redundancy of an observation is expressed by its redundancy number *Rii*, which is the ith diagonal element of R. The covariance of the residuals is equal to the covariance of the observations minus the covariance of the parameters, *Cx*, mapped into the observation space by the design matrix *A*, as Equation 2 shows:

$$C_{\hat{r}} = C_l - A C_{\hat{x}} A^T \qquad (2)$$

Cr is always less than or equal to Cl, meaning that Rii is always between 0 and 1. A redundancy value of 1 would mean that the observation is completely redundant and, thus, easily monitored for blunders. A redundancy value of 0 indicates that the navigation solution depends completely on the ith observation, making the identification of a blunder impossible.

To detect a blunder, each residual can be statistically tested where the null hypothesis, *Ho*, is that the residual is unbiased while the alternative hypothesis, *Ha*, is that the residual is biased. If a good observation is rejected, a *type one error* occurs. The probability of this is denoted by ***a***. A *type two error* occurs when a blunder is accepted into the solution. The probability of committing a type two error is denoted with ***b***. Choosing values of a and b determines a bias or non-centrality parameter of Ha and is denoted by ***do***. The marginally detectable blunder for observation *i*, can then be obtained by multiplying do by the covariance of the residual and dividing by the redundancy number, as shown in Equation 3:

$$|\nabla_i| = \frac{\delta_o \sqrt{C_{r_{ii}}}}{R_{ii}} \qquad (3)$$

Since each residual has a different covariance and each observation has a different redundancy, each observation has a different MDB. Assuming only one blunder occurs in a given measurement epoch, the maximum effect of one undetected blunder can be determined by evaluating the effect of each marginally detectable blunder on the navigation solution shown in Equation 4:

$$\ddot{A}X = -\left(A^T C_l^{-1} A\right)^{-1} A^T C_l^{-1} \nabla \qquad (4)$$

where ∇ is a column vector of zeros except for the ith row, which contains the marginally detectable blunder of the ith observation.

Reliability can then be quantified by the maximum position error (PE, or HPE in the horizontal plane) due to a single MDB. This is obtained by evaluating *ΔX* for each observation's MDB. This concept of reliability is closely associated with that of receiver autonomous integrity monitoring (RAIM).

Obviously, the reliability measure depends heavily on the redundancy of the solution. With the current GPS constellation, more than 4 satellites are almost always in view, often as many as 9 or 10. In these cases the reliability of GPS alone is generally good. However, in environments with limited satellite visibility, frequently not enough satellites are available for a reliable solution. The proposed Galileo constellation suffers from the same limitations. Used together, however, the two systems will provide enough availability to ensure a reliable solution even in extreme masking environments.

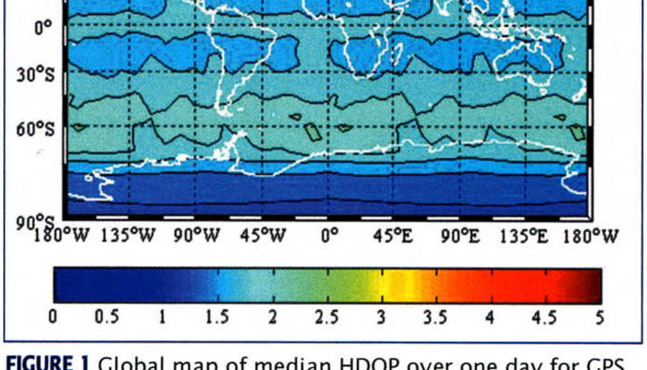

FIGURE 1 Global map of median HDOP over one day for GPS only using a 30° elevation mask and a height constraint

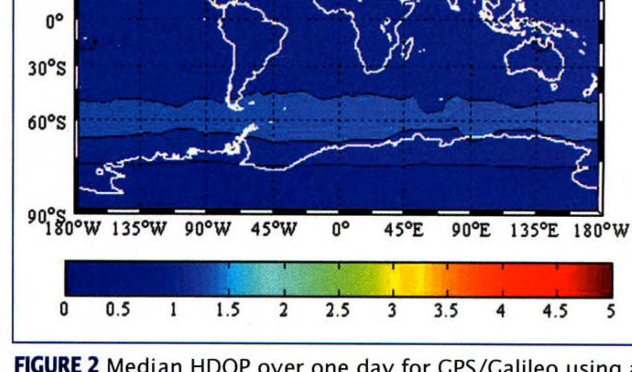

FIGURE 2 Median HDOP over one day for GPS/Galileo using a 30° elevation mask and a height constraint

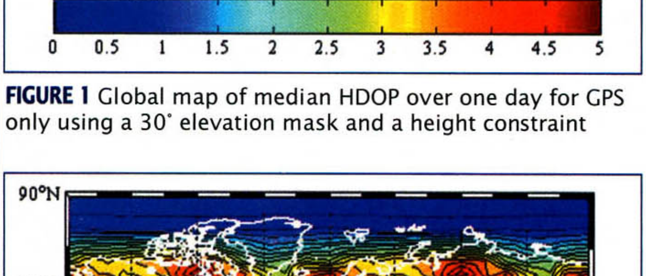

FIGURE 3 Median horizontal position error (HPE) due to one marginally detectable blunder (MDB) over one day for GPS using a 30° elevation mask and a height constraint

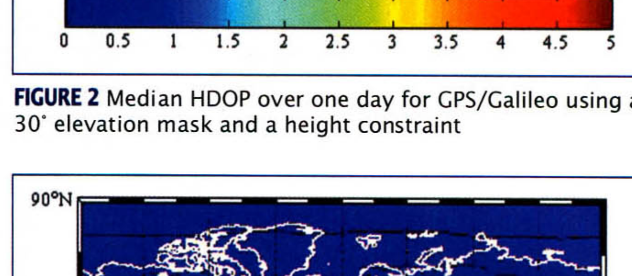

FIGURE 4 Median horizontal position error (HPE) due to one marginally detectable blunder (MDB) over one day for GPS/Galileo using a 30° elevation mask and a height constraint

the conditions of an urban user with a GPS receiver system that would use a map to obtain its height. The median horizontal DOP (HDOP) is lower than 2.5 everywhere in the world, which is still operationally good. The position accuracy can be simply obtained by multiplying the HDOP by a user-selectable UERE.

If we assume the use of a single-frequency receiver, the UERE must include the effect of the ionosphere. If a dual-frequency receiver is used, this ionospheric model is not required; however, the effect of receiver noise and multipath may be slightly higher, depending on how the ionospheric correction is derived. Assuming a UERE of 8 meters, which would be approximately the case of an L1 single-point user, the DRMS horizontal position error would not exceed 20 meters.

Figure 2 shows corresponding HDOP values for the combined GPS/Galileo case. The HDOP does not exceed 1.5, an incremental but significant gain with respect to stand-alone GPS. Although using both GNSSs noticeably increases nominal accuracies, combined GPS/Galileo shows dramatic improvements over GPS-alone when we consider reliability or fault detection capability.

The corresponding HPE results, which provide a reliability measure, are shown in Figures 3 and 4. We use a numerical value of 1 meter for the UERE, a reasonable number for the case of differential carrier phase–smoothed code positioning over a relatively short distance (between the reference station and the user). In the case of GPS alone, median horizontal position errors of up to 50 meters due to gross observation errors could occur and go undetected in regions of the world centered around latitude 65° N and 65° S, respectively. In other parts of the world, errors of up to 35 meters could occur and go undetected. When the combined solution is used, the corresponding median undetected errors that could occur do not exceed 3 meters in

most parts of the world and are below 6 meters everywhere.

Carrier Phase Ambiguity Resolution

Assessing the ambiguity-resolution capability through simulation is somewhat more difficult than determining accuracy and reliability performance because the former analysis requires the generation of actual observations with realistic errors. Ambiguity-resolution testing can then be carried out using an appropriate software package.

Performance measures must be defined. The two performance measures used herein are the time to fix ambiguities and the percentage of correctly determined ambiguity sets. Because each ambiguity-resolution software package and user employs its own options, the process is subjective, and absolute performance measures should be used with caution. However, provided the same options are used in both cases, the relative results between two simulations (for example, GPS-alone versus GPS/Galileo) will give a reasonable estimate of the performance difference.

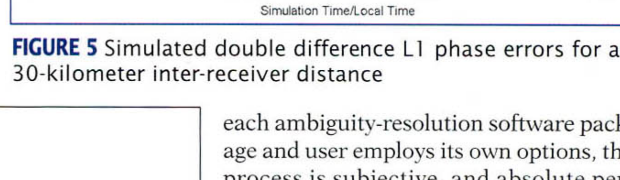

FIGURE 5 Simulated double difference L1 phase errors for a 30-kilometer inter-receiver distance

The time required to fix ambiguities is an important measure for users as it indicates the amount of time needed to achieve peak system accuracy. The time to fix is highly correlated to the second performance measure, which is the percentage of correctly determined ambiguity sets. An ambiguity set is defined as the collection of double difference ambiguities associated with the carrier phase measurements at a given epoch. Modifying processing software parameters can change the balance between time to fix and the percentage of correctly determined ambiguity sets. In general, increasing the minimum time prior to first fix can increase the percentage of correctly fixed ambiguities.

We employed a proprietary software-based GNSS observation simulator that uses complex models to generate orbit, ionosphere, troposphere, multipath, and receiver noise errors for the purpose of generating code and carrier phase observations. **Figure 5** shows simulated GPS L1 double-difference carrier phase–measurement range errors for a 30-kilometer inter-receiver separation (receivers are assumed to be stationary). The measurement range errors are 3 parts per million (ppm) of the inter-receiver distance, which agree well with typical errors observed under medium ionospheric conditions.

To compare the ambiguity resolution capabilities of GPS-alone versus GPS/Galileo, we generated simulations of code and carrier phase GPS and Galileo observations at nine points located in the central United States. We selected the points so as to provide a wide range of inter-receiver distances and azimuths. All 36 baselines formed

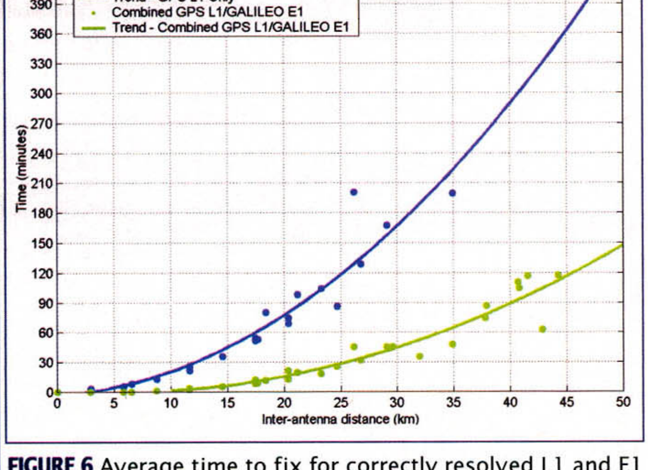

FIGURE 6 Average time to fix for correctly resolved L1 and E1 ambiguity sets

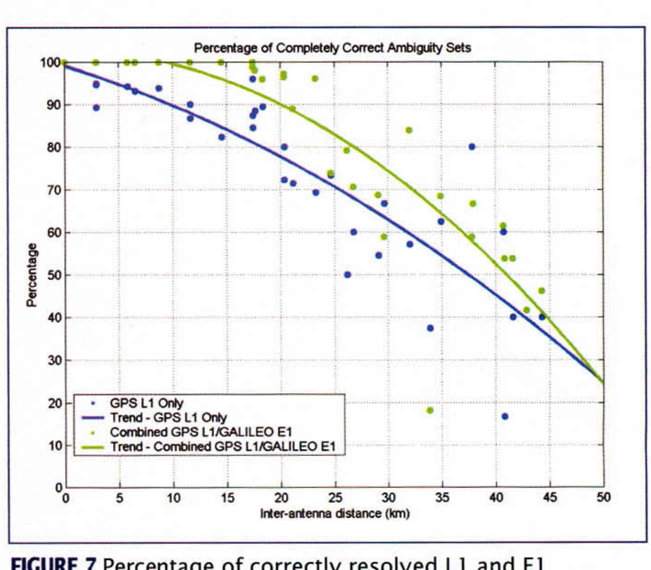

FIGURE 7 Percentage of correctly resolved L1 and E1 ambiguity sets

by the points were processed independently. The baseline lengths ranged from approximately 3 to 50 kilometers. Each baseline was processed in kinematic mode, estimating first the float ambiguities and positions. Each time the integer ambiguities were successfully resolved, the ambiguity and position estimates were reset to start a new solution in order to obtain independent samples of the ambiguity resolution performance.

Figure 6 shows the average time to fix L1 ambiguities correctly for GPS and GPS/Galileo. (Note that we included only baselines in which integer ambiguities were fixed correctly more than four times were included so as not to bias the results with outliers.) The combined system achieves the same ambiguity resolution performance as GPS at twice the baseline length.

Although the time-to-fix is important, the proportion of correctly fixed ambiguities is also crucial for successful RTK field operations. Thus, the percentage of correctly fixed ambiguity sets, shown in **Figure 7**, constitutes another important performance measure. The performance of the combined system is about 10 percent better than that of GPS alone in this single-frequency case. With roughly twice as many satellites as GPS, a combined system is better able to reject incorrect ambiguity sets. Performance decreases as the inter-receiver distance increases because differential errors increase as a function of distance. As a result, as the errors and associated biases approach half a wavelength (about 10 centimeters on L1) the wrong integer ambiguity set is more likely to be selected by the search algorithm.

Position solutions also become more accurate as a consequence of improved satellite availability. Redundant observations can average measurement noise more effectively and make the position solution more precise. For example, the position results for a fixed-ambiguity L1 GPS and L1/E1 combined system are shown in Figure 8 for a 12-kilometer baseline. The 3D RMS errors are 3.8 and 2.6 centimeters, respectively. These errors are mostly due to the effect of the ionosphere on single frequency observations, even when the L1 integer ambiguities are fixed. In this case, the use of the

combined system results in an accuracy improvement of 32 percent compared to that of GPS alone.

Many options exist for position processing and ambiguity resolution when incorporating all frequency observations from both systems. One method is to use a cascading scheme whereby frequency combinations are constructed that provide the best wavelength-to-observation-error ratios, which can then be processed consecutively until all ambiguities are fixed to their integer values. Following this, ionospheric-free observables can be formed if the effect of the ionosphere warrants it. Another methodology estimates all ambiguities in parallel and determines the frequency combinations that are statistically most likely to be successfully resolved. This must be done using accurate covariance information. These methods are similar in that various frequency combinations are used in combination to assist in the resolution of the shorter wavelength ambiguities.

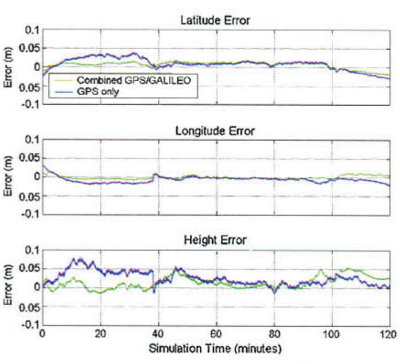

FIGURE 8 Single frequency fixed ambiguity position errors for GPS and GPS/Galileo – 12 km inter-receiver distance

Three-frequency GPS II and Galileo will also provide an advantage for long-baseline users because of the ability to estimate ionospheric effects. The added ionospheric observability of three-frequency GNSSs will reduce observation biases and, therefore, enable faster ambiguity resolution and better position accuracy over medium and long inter-receiver distances.

Discussion of these latter approaches is beyond the scope of this article. However, it seems intuitively obvious that, used in conjunction with both systems simultaneously, such methods will provide a level of ambiguity resolution performance undreamed of until now. ⊕

Further Reading

For a detailed discussion of reliability theory:

Parameter estimation and Hypothesis Testing in Linear Models, second edition, by K. Koch, New York, Springer-Verlag, 1999.

Galileo web site: www.europa.eu.int/comm/energy_transport/en/gal_en.html

Galileo signal structure is described in: www.europa.eu.int/comm/energy_transport/library/gal_stf_final_paper.pdf

More information on work related to this topic: www.geomatics.ucalgary.ca/research/GPSRes/first.html (Project #24)